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# Assessing the Threat of Undersampled Ionospheric Irregularities for Wide Area Differential GPS Systems

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# Outline

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- **WAAS requirements**
- **Nature of the ionospheric threat**
- **Methodology for assessing threat**
- **Case analysis**
- **Results of data deprivation studies**
  - deprivation by annular regions
  - deprivation by rectangular boundaries
- **Conclusion**



# WAAS Requirements



- **Performance requirements**
  - Positioning accuracy goals available over space and time
- **Integrity requirements**
  - Position error bounds are faithful
  - Analytical “proof” that system is safe
  - Analysis requires well-established assumptions



## Nature of ionospheric threat



- Finite sampling of ionospheric medium
- During disturbed periods, delays can reach 40m vertical
- Highly structured
- Irregularity detector is part of the algorithm



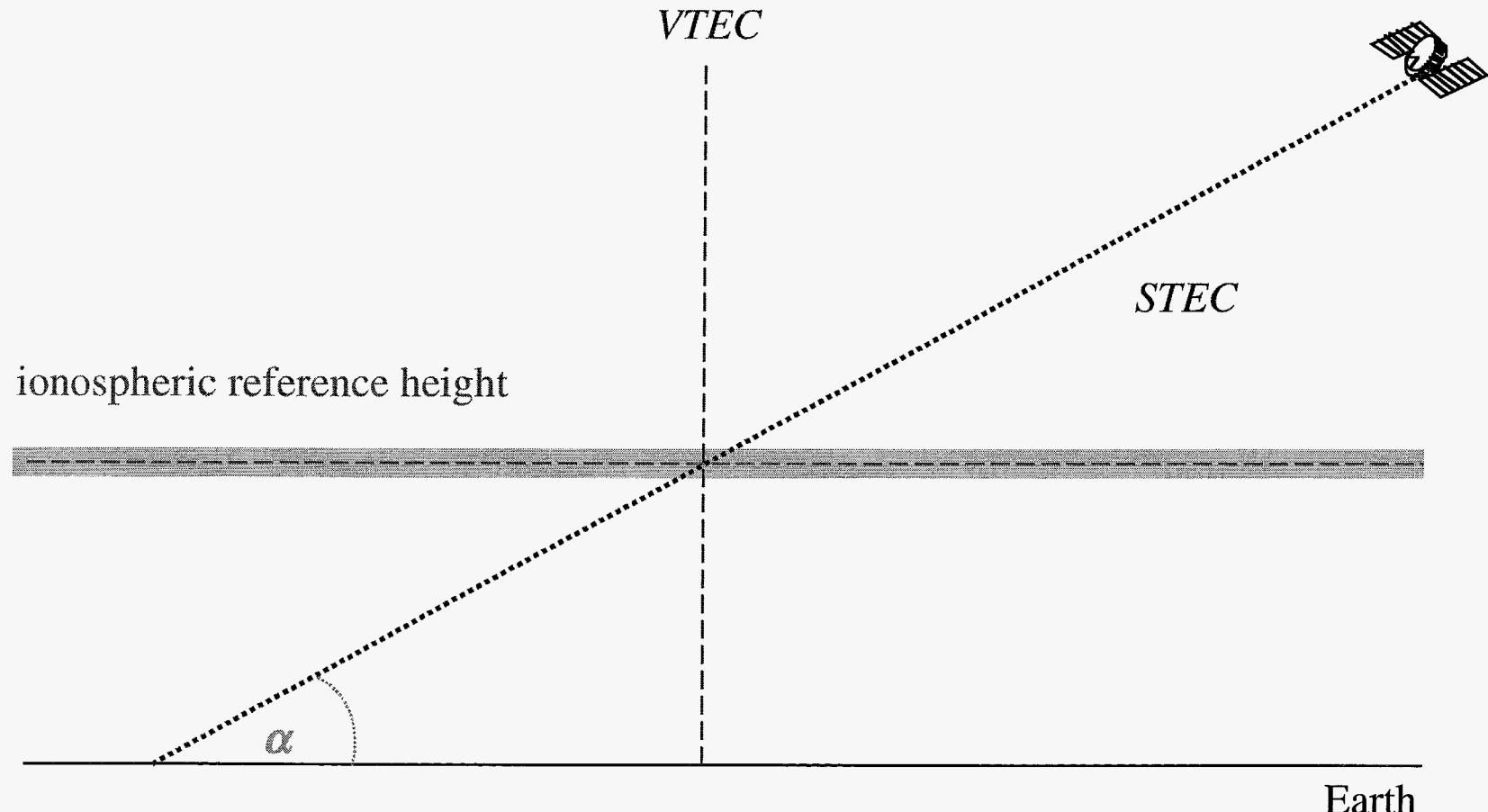
# Identifying Threatening Geometries



- Data deprivation studies reveal edge represents significant threat
- Real-time algorithm must identify areas where threat is potentially highest
- Threat model adjusts error bound in real-time to ensure integrity under all conditions



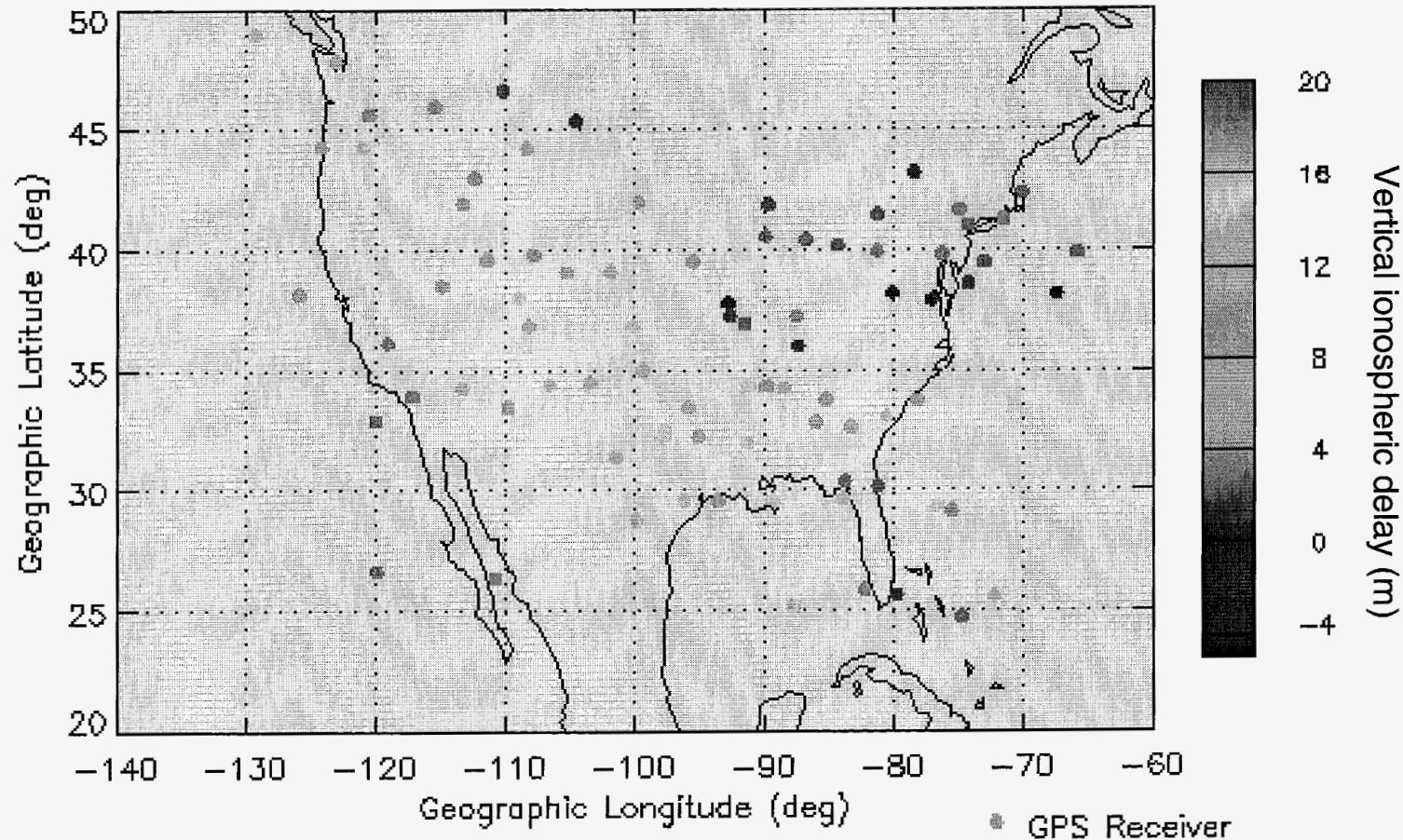
## Thin-shell model



Vertical ionospheric delay is modeled using the thin shell approximation.



## Distribution of measurements for one epoch



Color gives magnitude of delay at ionospheric pierce points (IPPs) in one epoch.



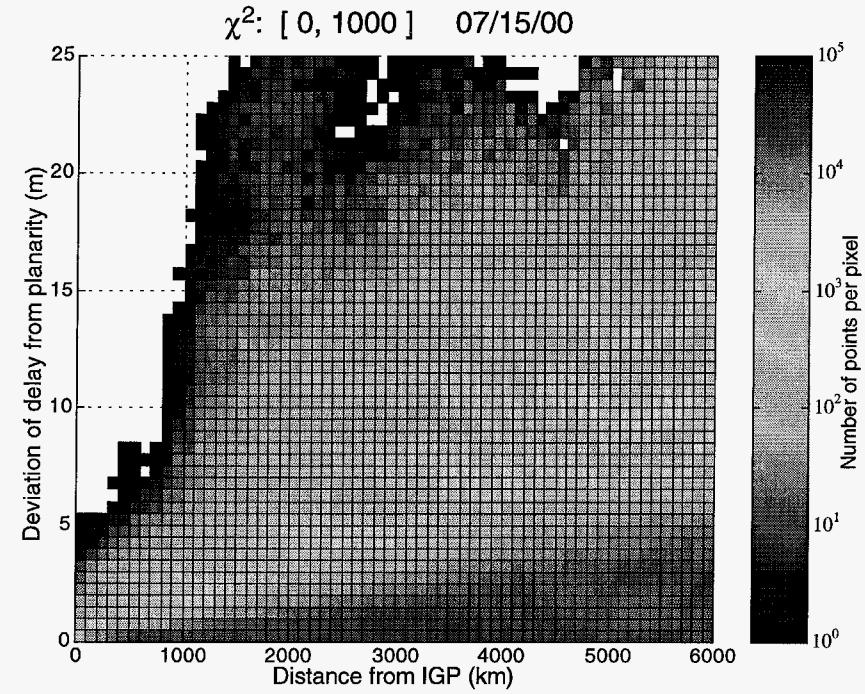
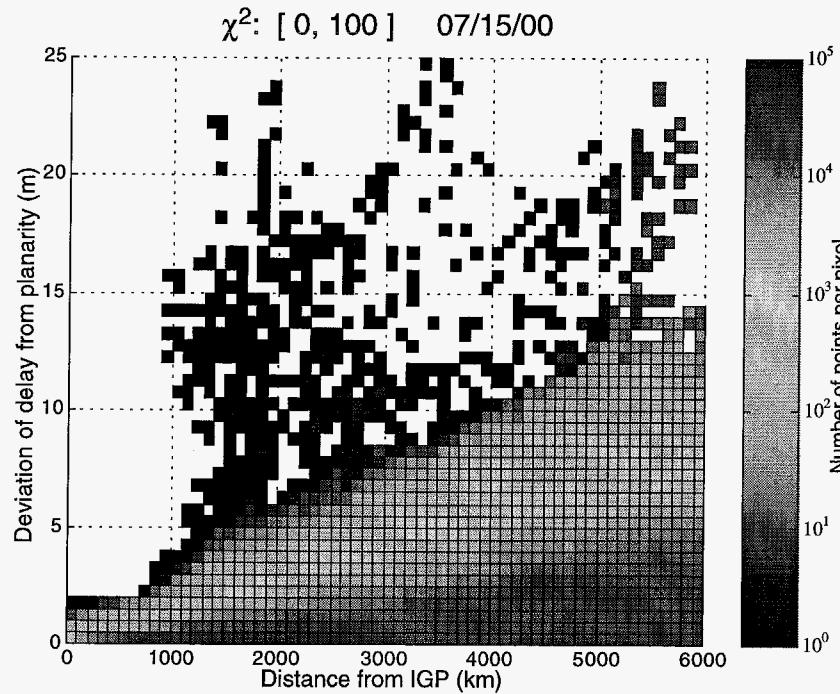
## Algorithm for correlation analysis



- Define WAAS grid and rotation matrices [ (x, y, z) -> (e, n, u) ] at each IGP
- Select data from one epoch (*i.e.*, one time-tag)
- Calculate obliquity factors
- Convert each IPP position to xyz coordinates
- Loop over WAAS IGPs
  - Sort epoch data by distance to IGP
  - Perform planar fit with 30 nearest points (within 2100 km)
  - Tabulate deviations from planarity inside *threat* domain:
    - as function of  $\chi^2$  (or  $\chi^2/\chi^2_{\text{threat}}$ )
    - as function of metric (distance from IGP, fit radius, hole size)



# Dependence on irregularity detector



$$\chi^2 < 100$$

$$\chi^2 < 1000$$

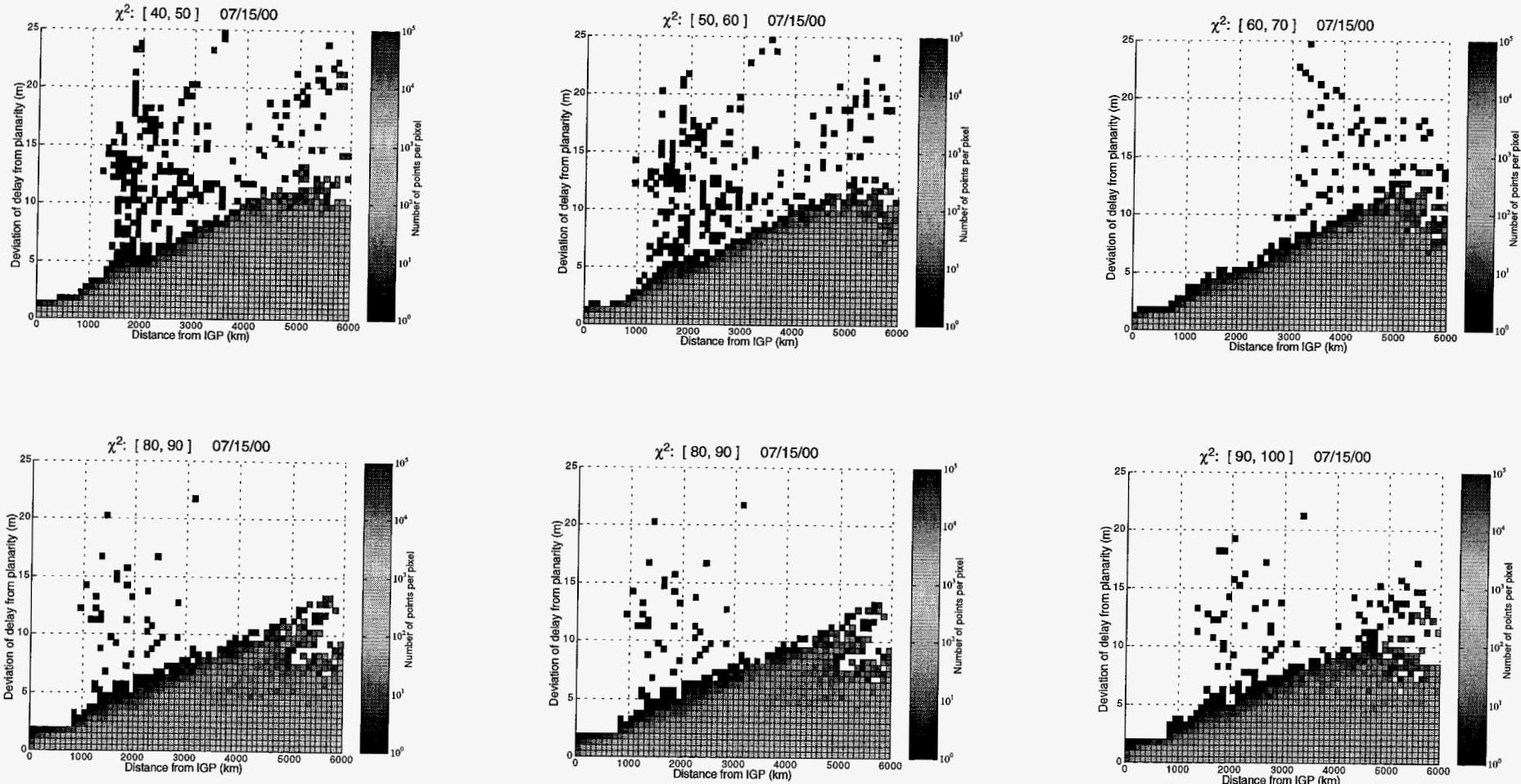
The threat domain is here the entire WAAS grid.

More sample points are included same  $\chi^2$  bins.



# Storm time (7/15/00) decorrelation plots

## $\chi^2$ range: [40, 100]

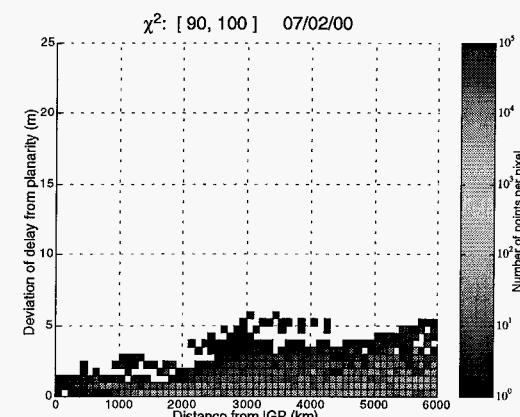
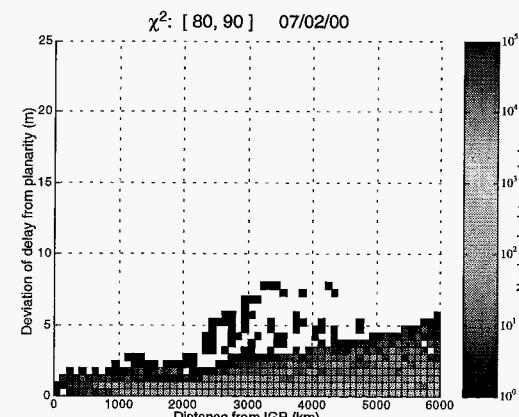
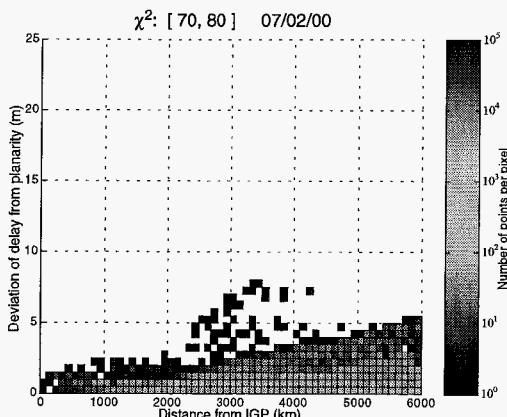
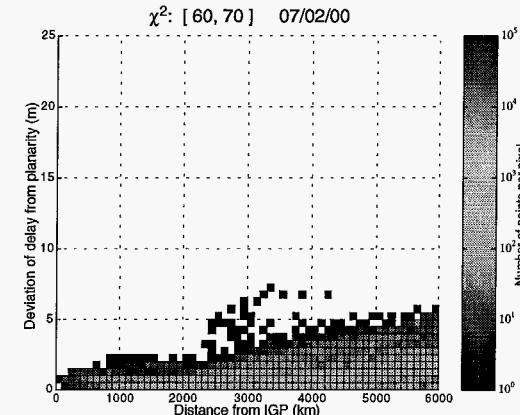
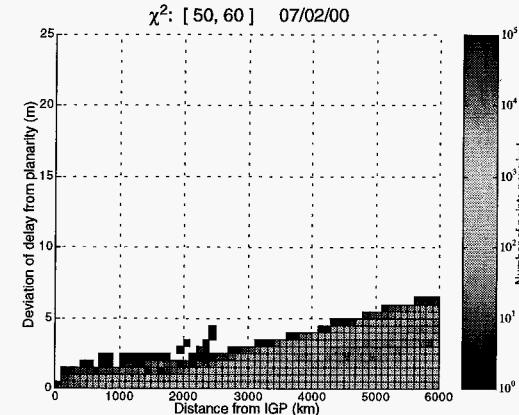
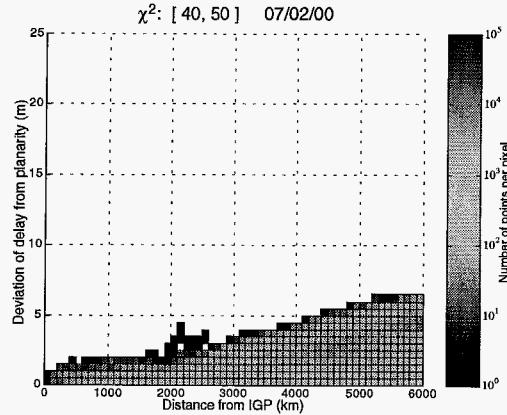


Dependence on  $\chi^2$  is weak.



# Quiet time (7/2/00) decorrelation plots

## $\chi^2$ range: [40, 100]

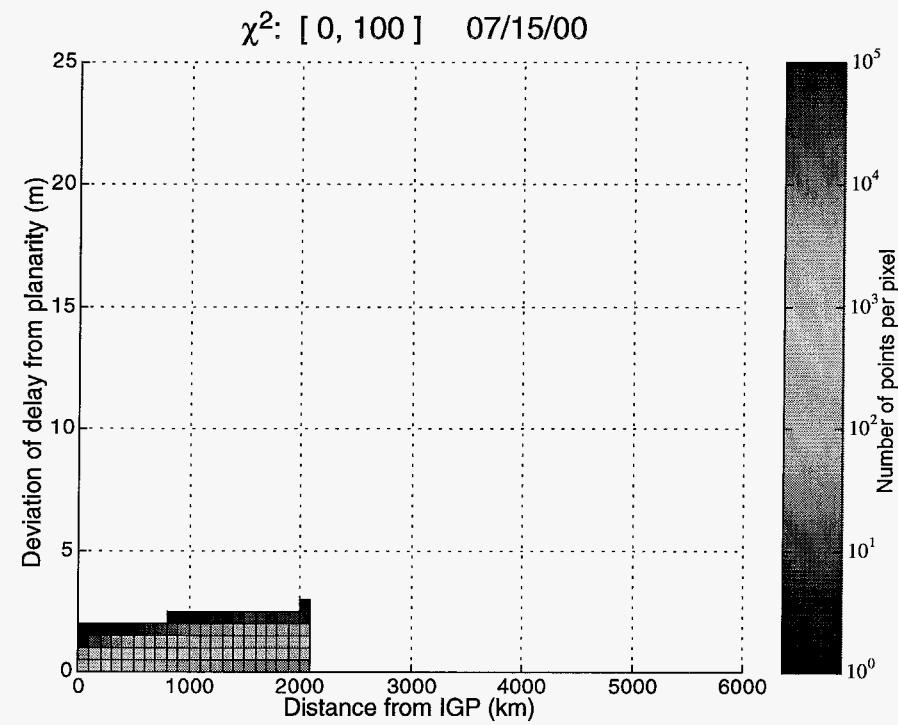
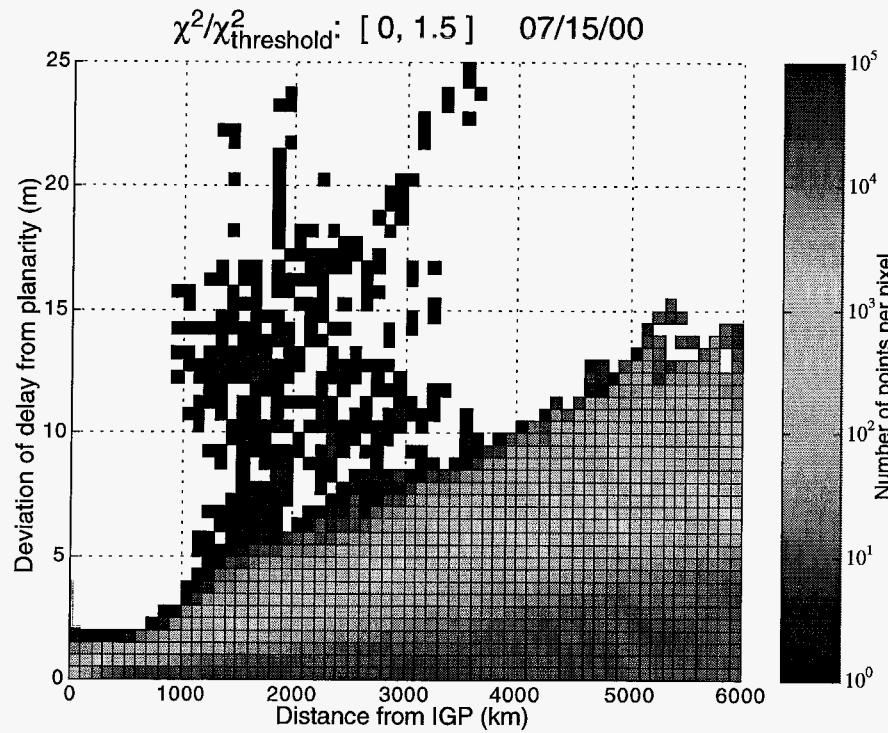


Figures are similar to storm time for distances < 1000 km.





# Comparing different threat domains

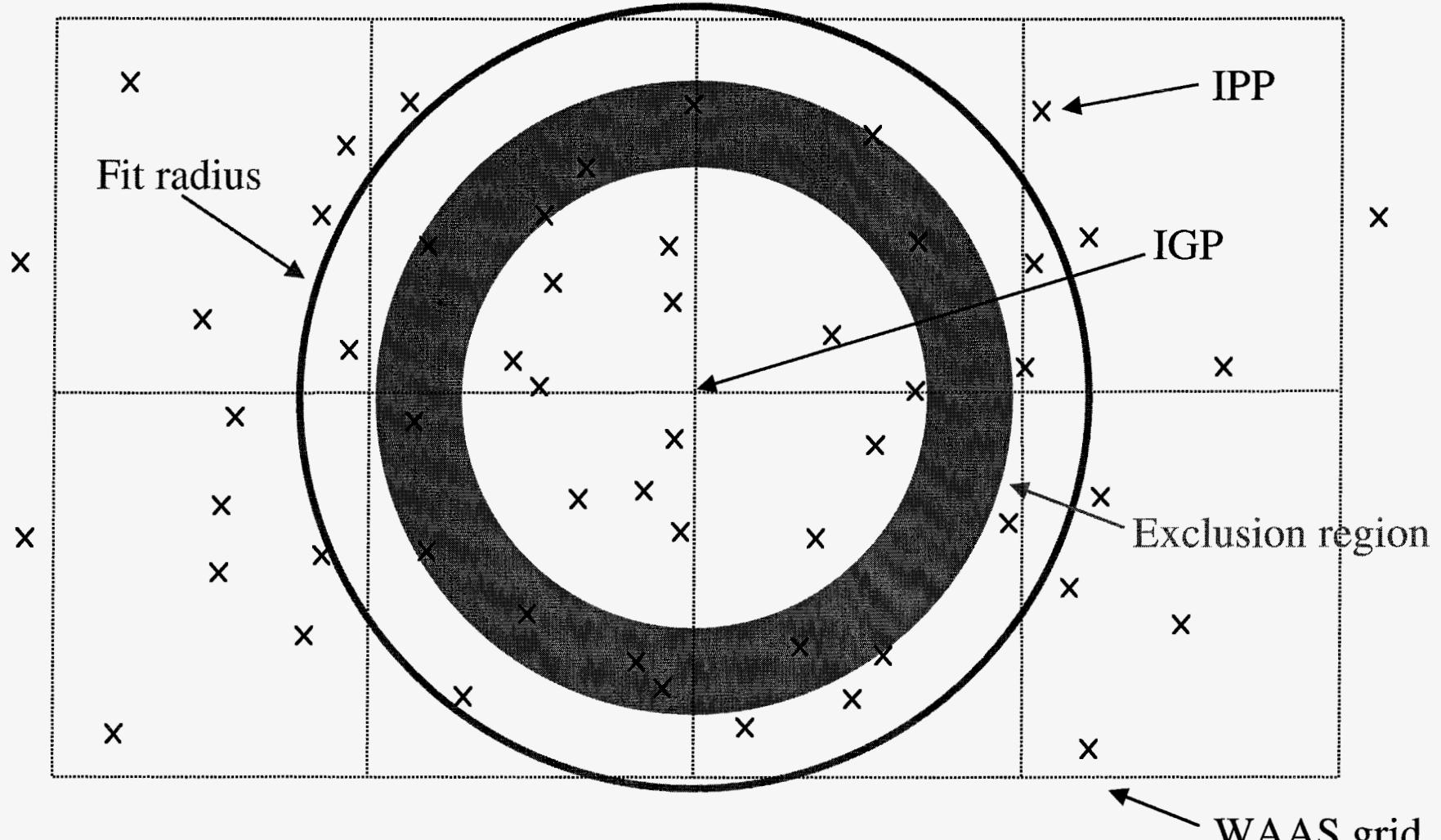


The threat domain is the entire WAAS grid.

The threat domain is the fit radius.



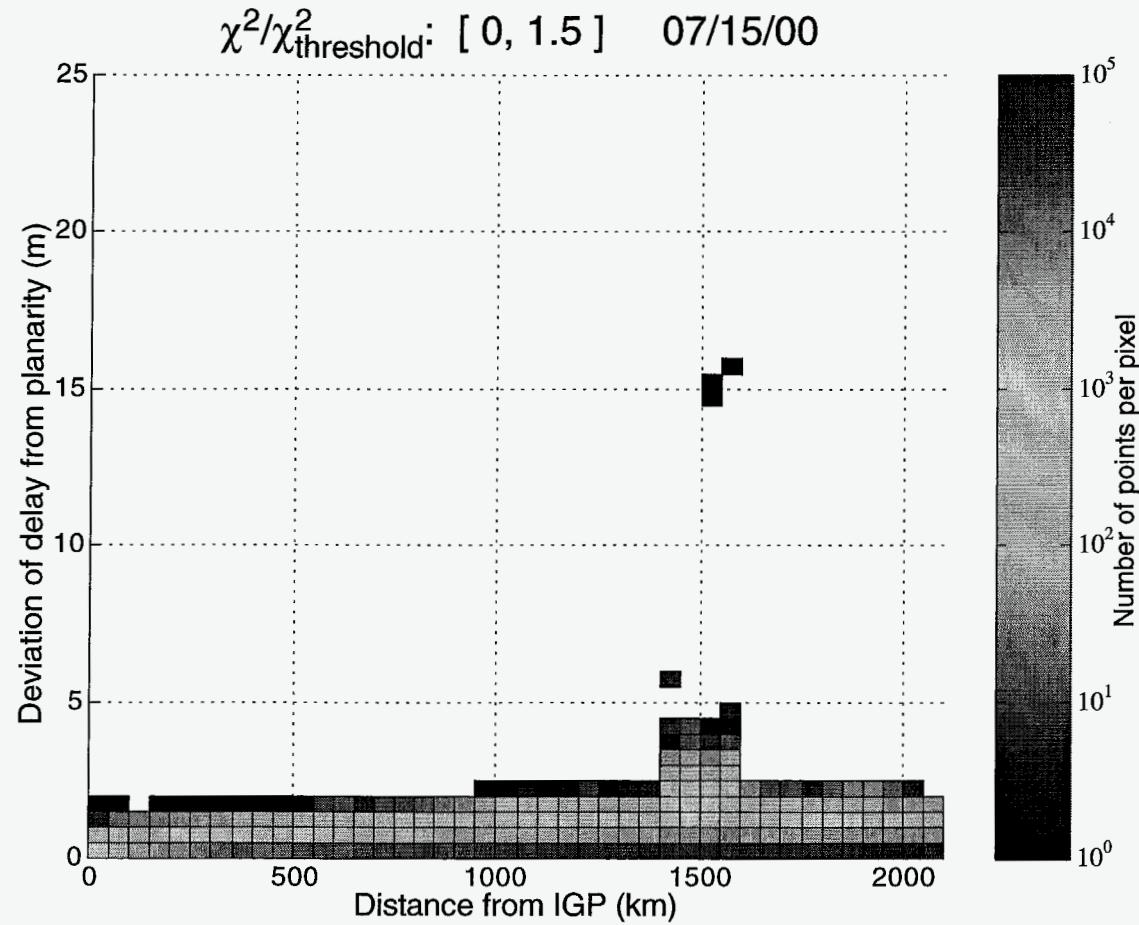
## Data deprivation studies



Exclude from fit the IPPs that reside within an annulus.



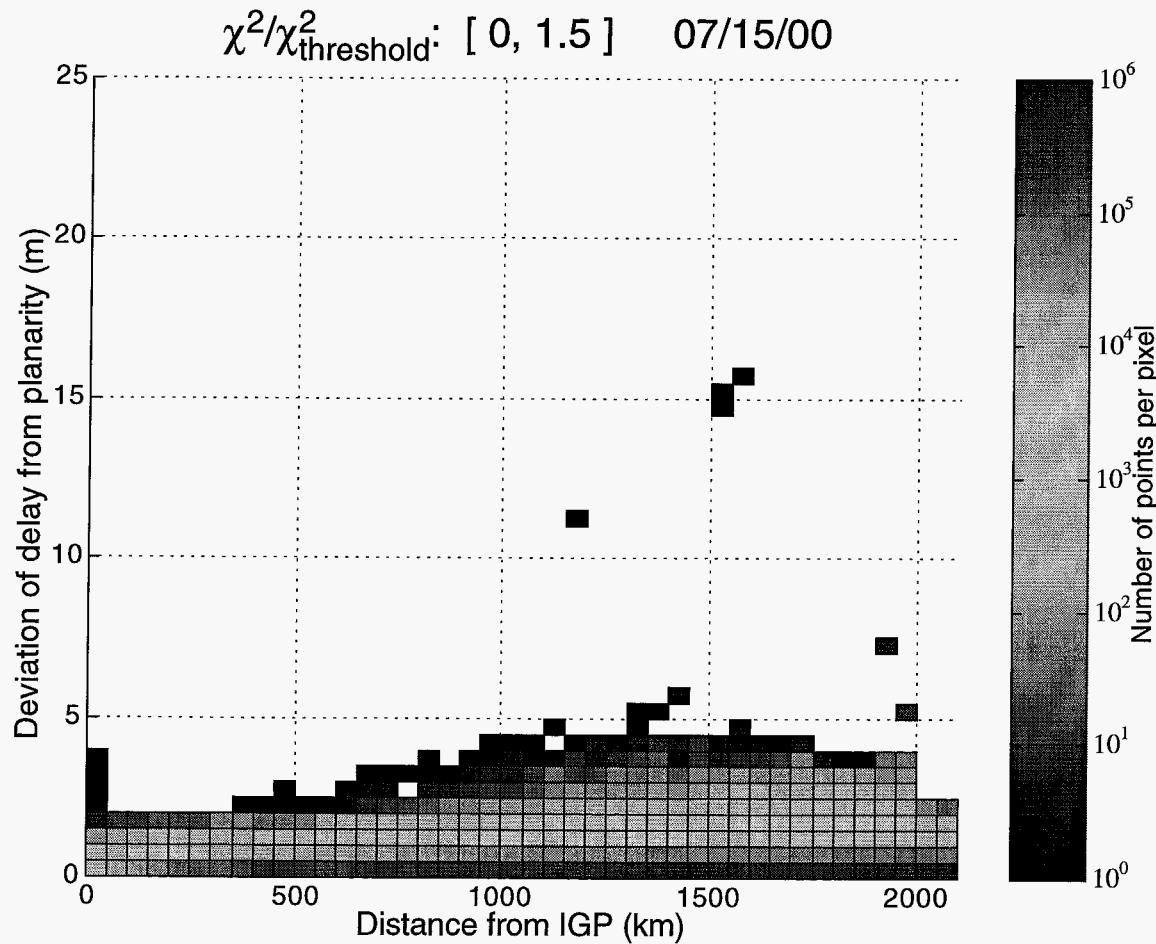
## Excluding data from one annulus



IPPs are excluded that lie in the range 1400-1600 km.



# Accumulating results for a series of data deprivation studies

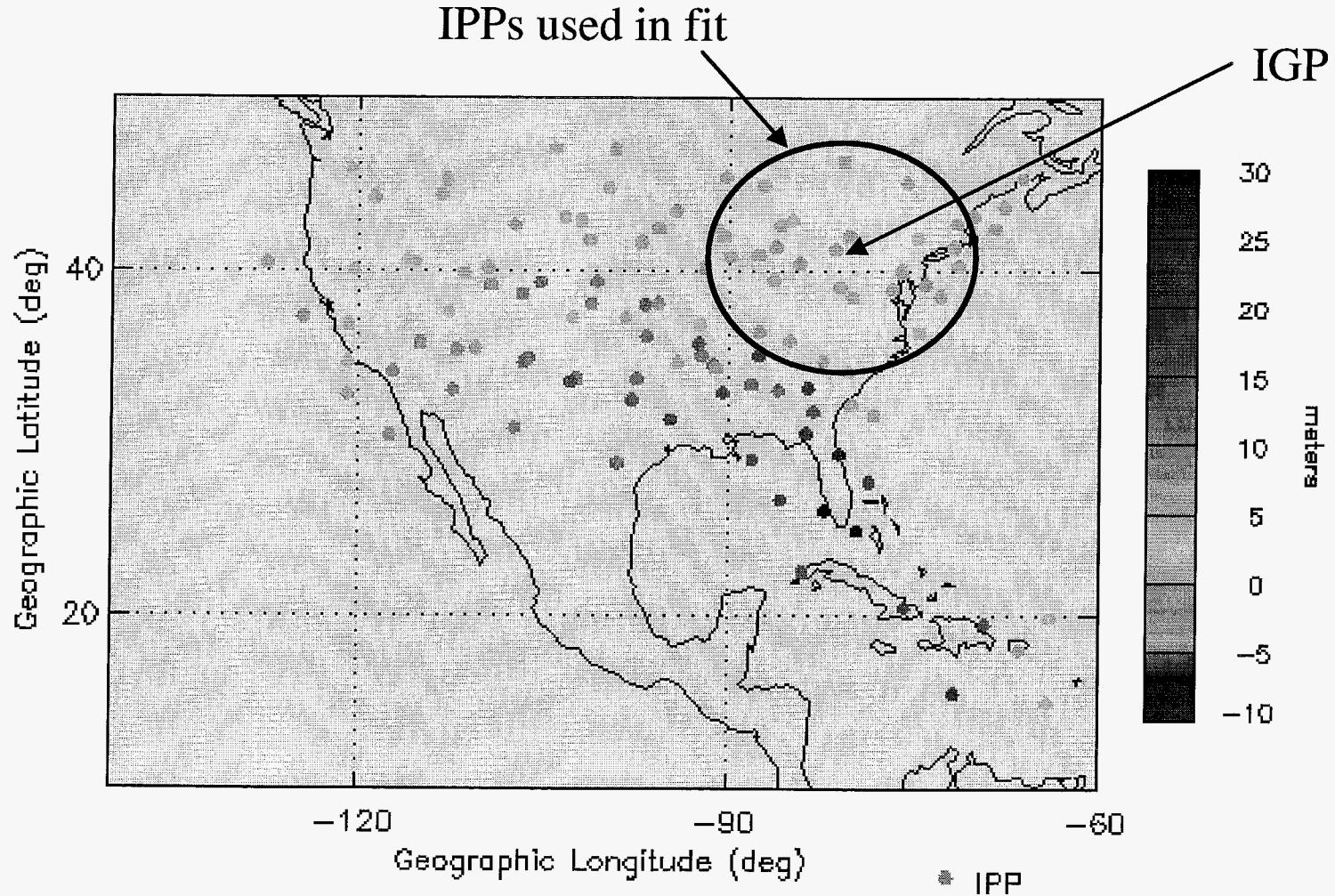


Data are excluded in a succession of annuli, each with 200 km width.



# Deviations from Planarity

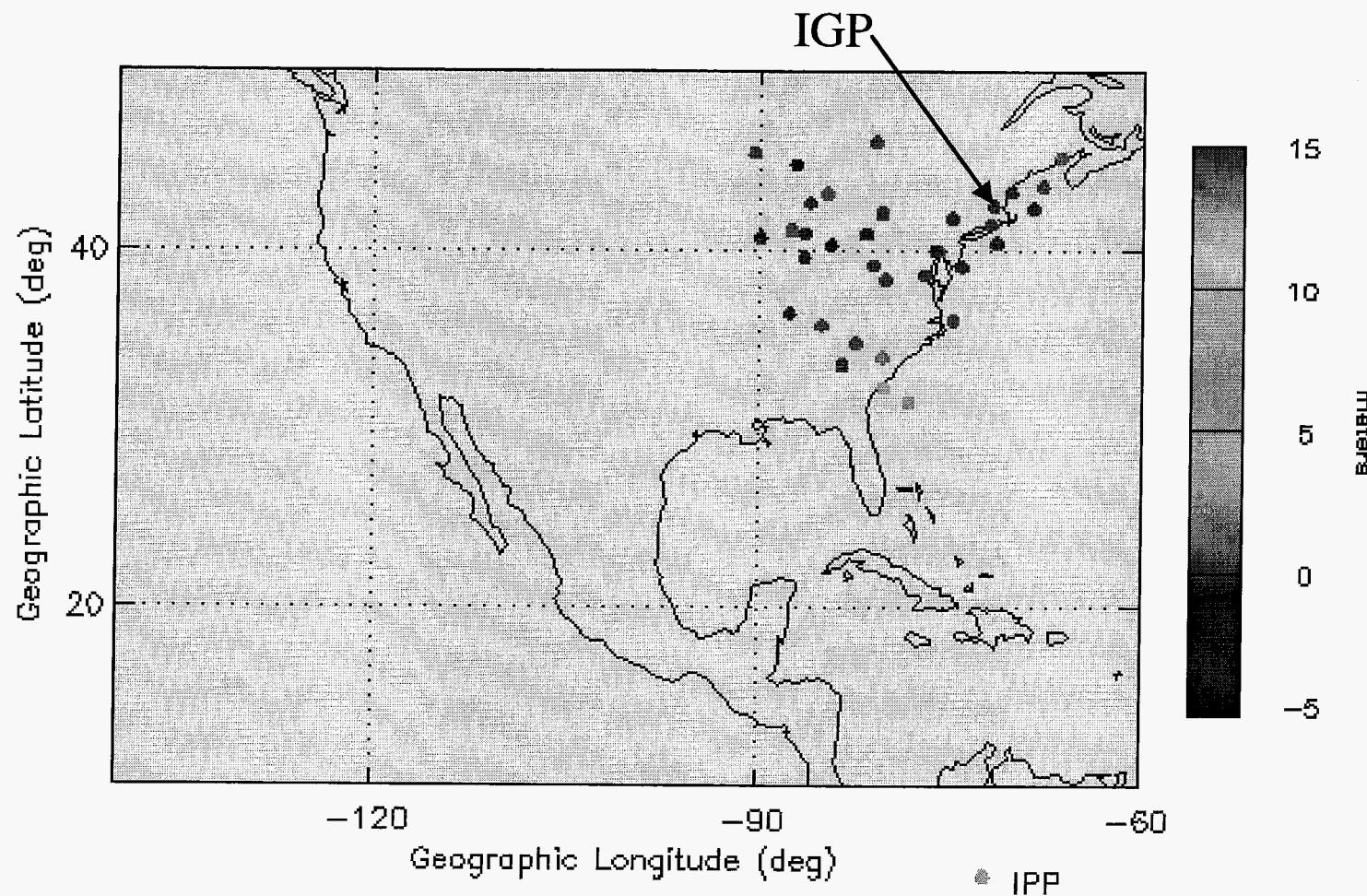
## July 15, 2000, 23:50 UT



Undetected sharp gradients can exist next to undisturbed regions.



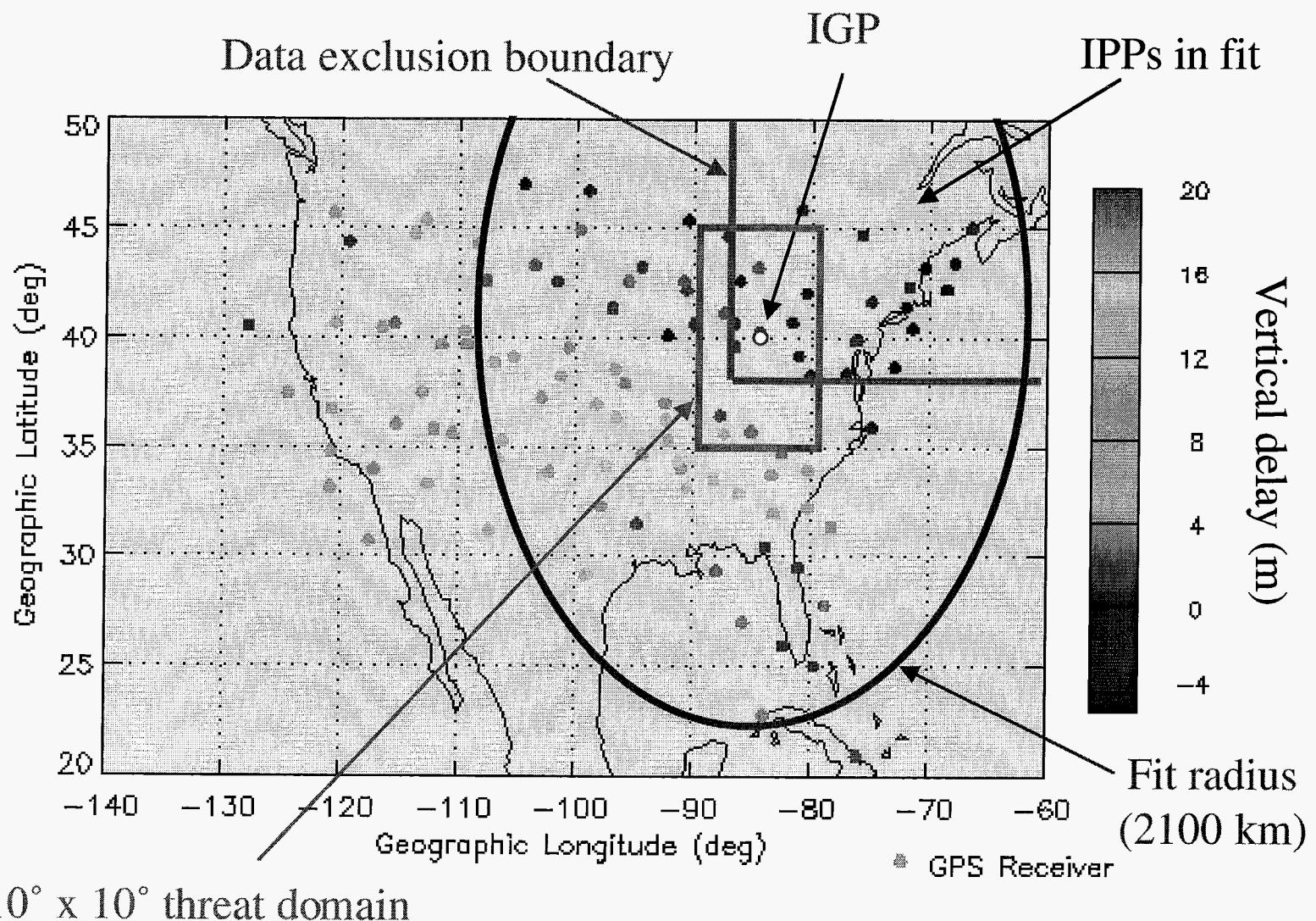
# Deviations from planarity with the fit radius July 15, 2000, 23:47 UT



An undetected gradient within the fit domain represents a potential major threat.

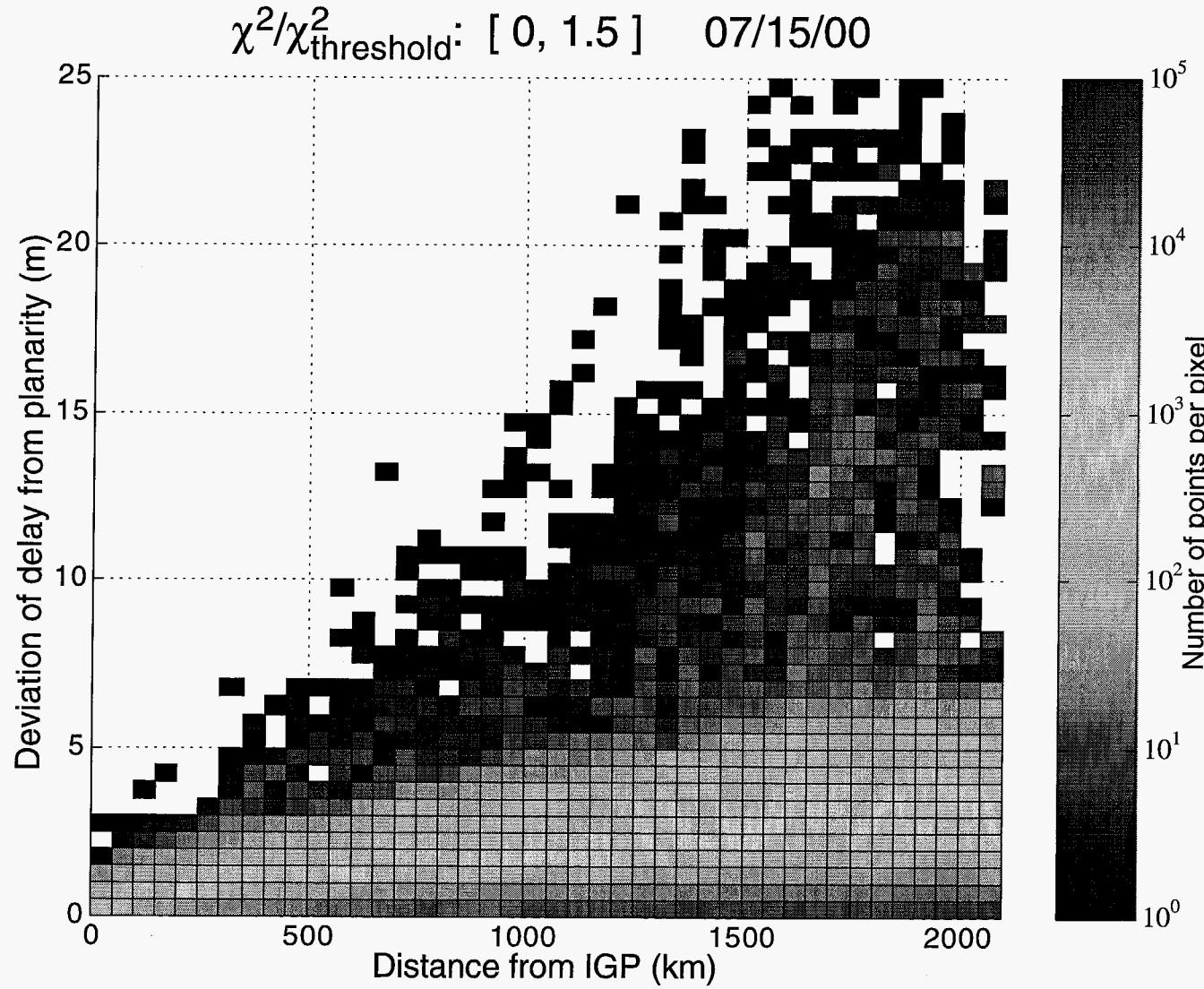


## Data deprivation: an example



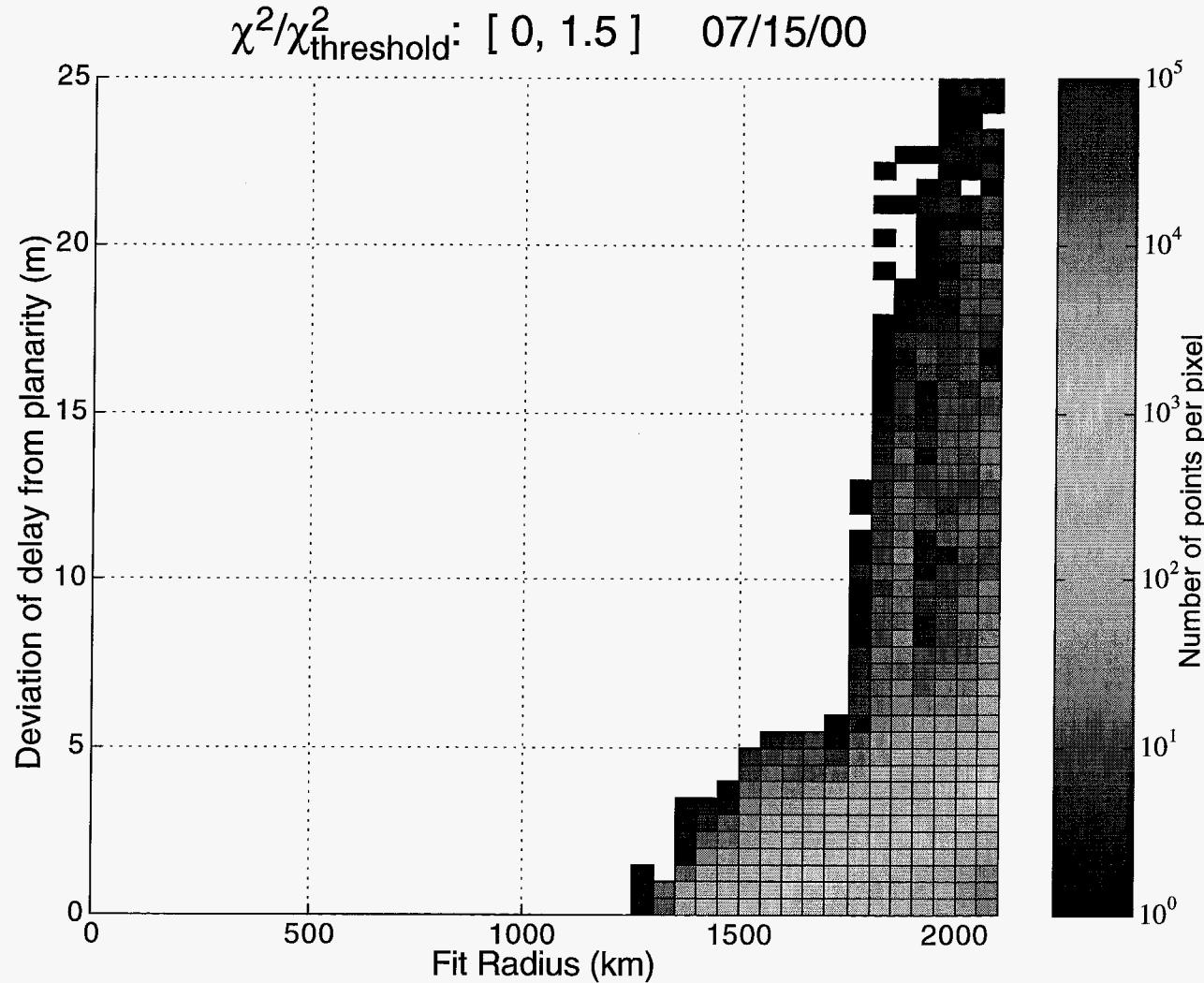


## Excluding from fit all data east and south of IGP



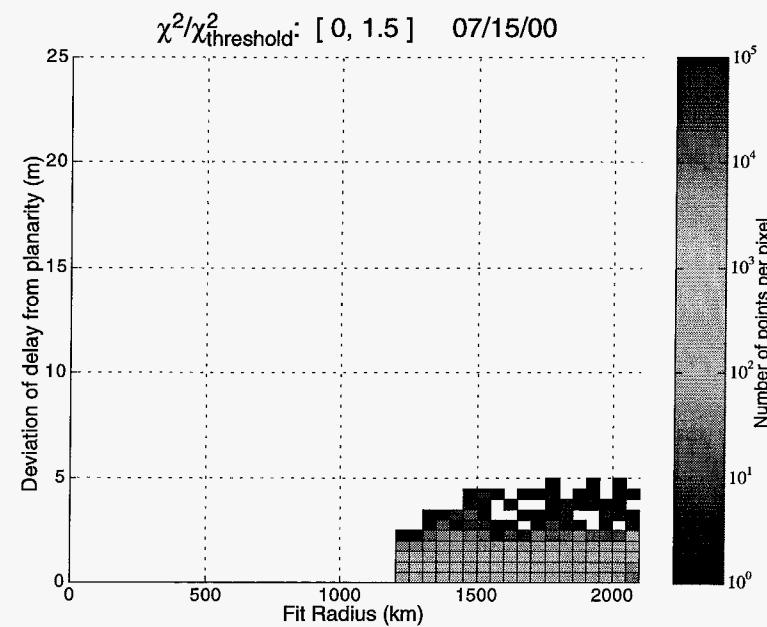
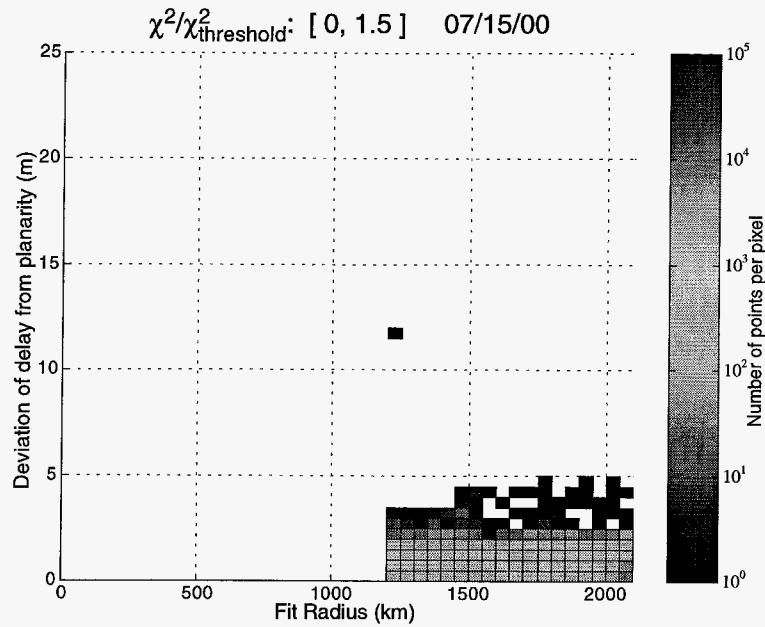


## Tabulating deviations vs. fit radius





# Excluding from fit the band 1000 - 1200 km and plotting vs. fit radius

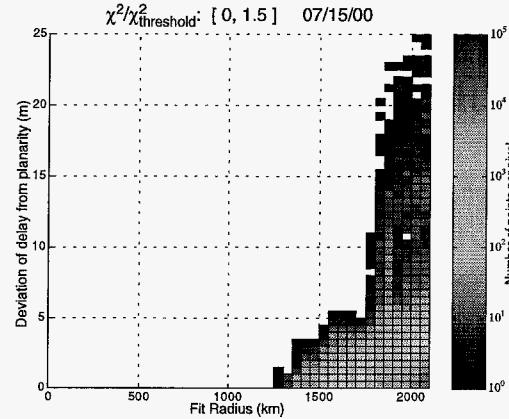


Tabulating data within  
fit radius

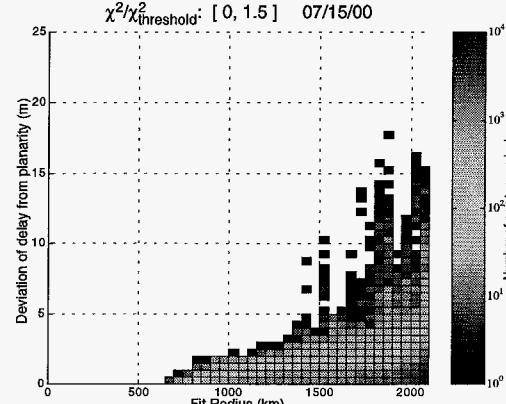
Tabulating data within  
fit radius - 200 km



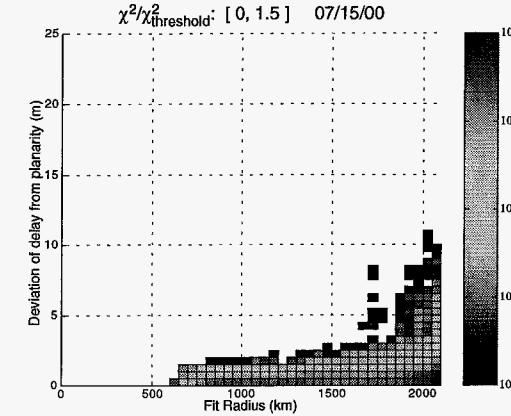
# Tabulating points within threat radius (fit radius = 200 km): expanding fit domain in $1^\circ$ increments



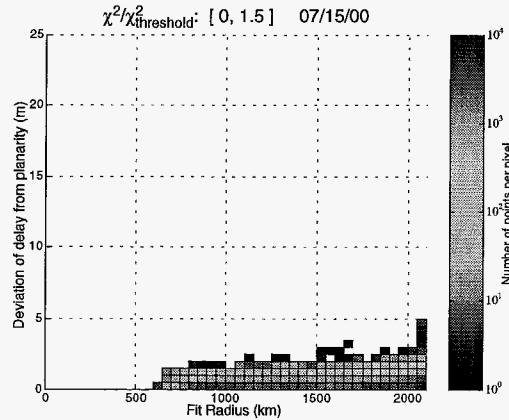
+  $0^\circ$  east and south of IGP



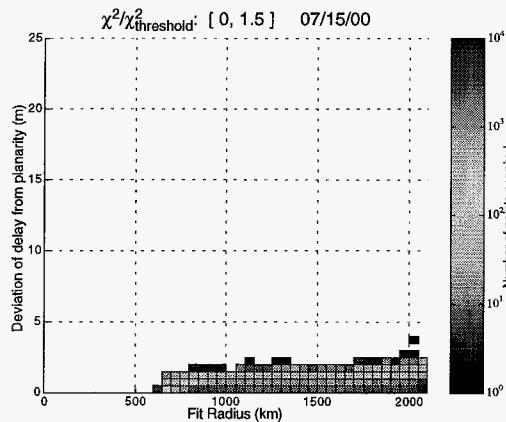
+  $1^\circ$  east and south of IGP



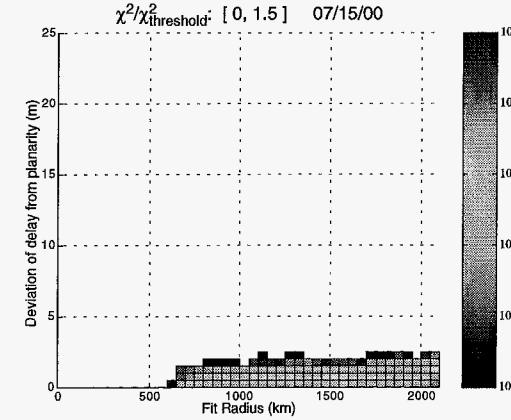
+  $2^\circ$  east and south of IGP



+  $3^\circ$  east and south of IGP



+  $4^\circ$  east and south of IGP



+  $5^\circ$  east and south of IGP